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(54) **MULTI-ROBOT GRADIENT BASED  
ADAPTIVE NAVIGATION SYSTEM**

(56) **References Cited**

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U.S. PATENT DOCUMENTS

3,764,964	A *	10/1973	Seeley, Jr. ....	G01S 3/808 342/374
6,266,577	B1 *	7/2001	Popp .....	B25J 9/163 700/245
6,374,155	B1 *	4/2002	Wallach .....	G05D 1/0274 700/245
6,636,781	B1 *	10/2003	Shen .....	B08B 9/045 318/568.11
7,966,093	B2 *	6/2011	Zhuk .....	G05D 1/0088 700/245
8,577,538	B2 *	11/2013	Lenser .....	G05D 1/0274 701/2
8,632,376	B2 *	1/2014	Dooley .....	A63F 9/143 273/246
8,809,755	B1 *	8/2014	Patel .....	F42B 19/06 244/3.26
8,838,292	B2 *	9/2014	Palm .....	G05D 1/0289 701/2
8,996,224	B1 *	3/2015	Herbach .....	G05D 1/0011 180/116
9,043,069	B1 *	5/2015	Ferguson .....	B60W 30/00 701/23
9,261,578	B2 *	2/2016	Im .....	G01S 5/0252
9,315,248	B2 *	4/2016	Williams .....	B63G 8/001
2004/0030449	A1 *	2/2004	Solomon .....	B64C 39/024 700/245
2004/0162638	A1 *	8/2004	Solomon .....	F41H 13/00 700/247
2006/0015215	A1 *	1/2006	Howard .....	G05D 1/0094 700/245
2007/0156286	A1 *	7/2007	Yamauchi .....	G05D 1/0038 700/245

**Related U.S. Application Data**

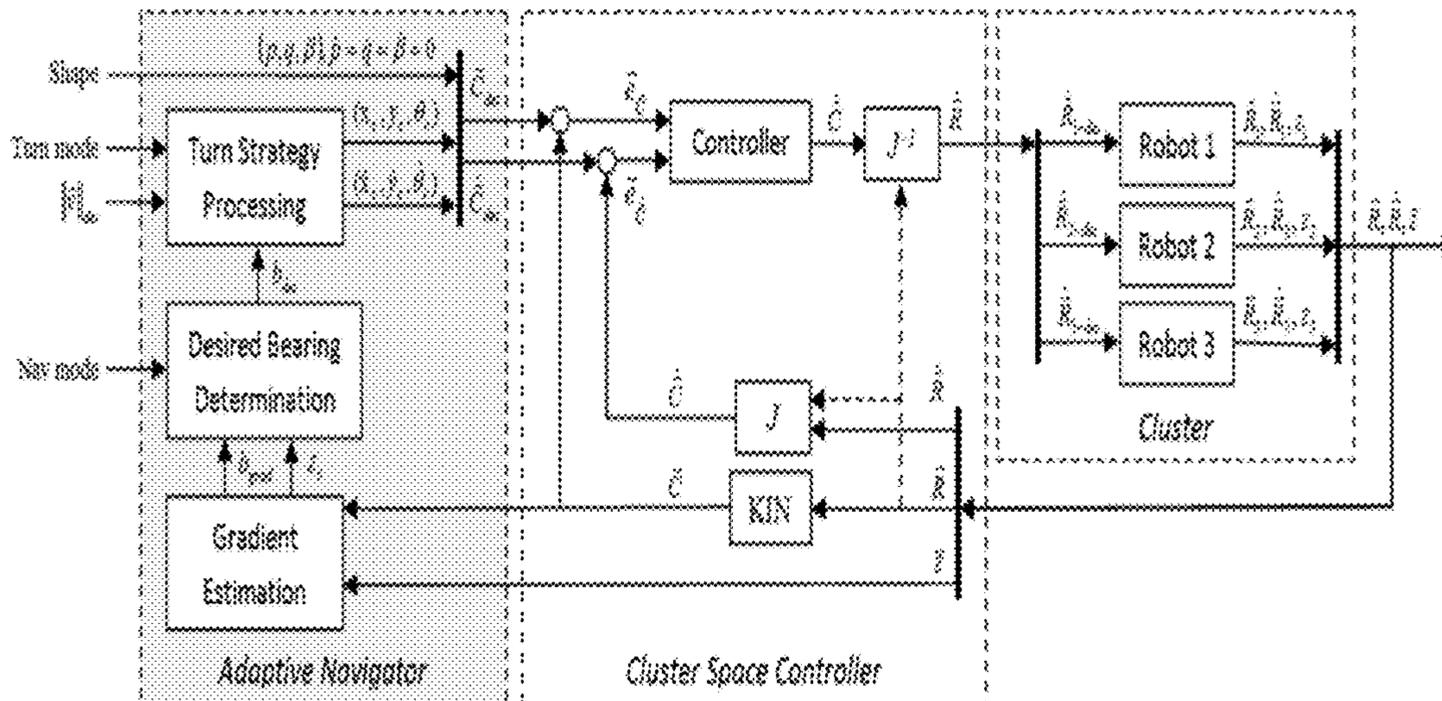
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(57) **ABSTRACT**  
Systems and methods for multi-robot gradient-based adaptive navigation are provided.

**1 Claim, 1 Drawing Sheet**



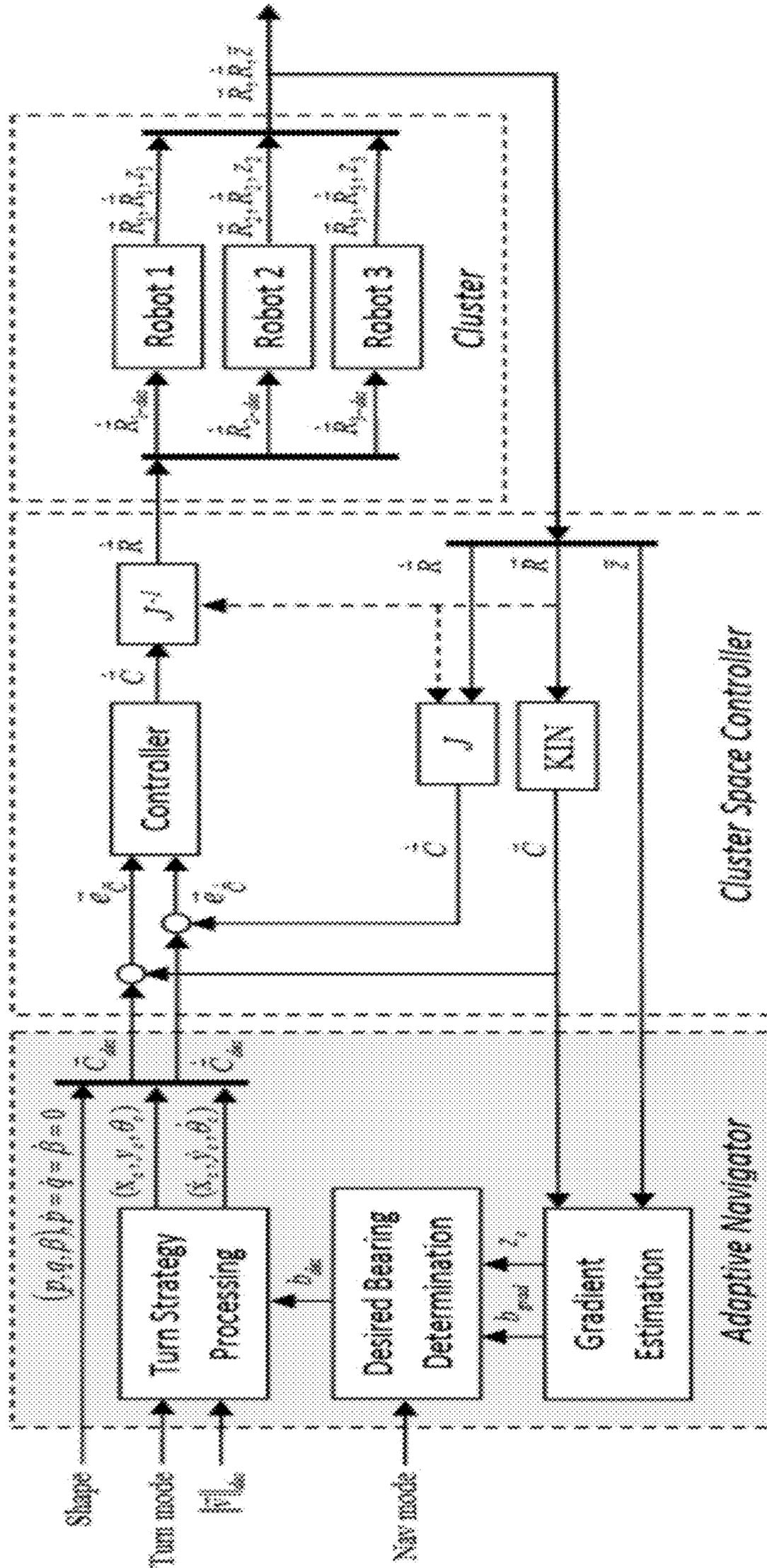
(56)

**References Cited**

U.S. PATENT DOCUMENTS

2007/0168117 A1\* 7/2007 Howard ..... F41G 3/04  
701/425  
2007/0233337 A1\* 10/2007 Plishner ..... G05D 1/0295  
701/23  
2008/0027591 A1\* 1/2008 Lenser ..... G05D 1/0251  
701/2  
2009/0000860 A1\* 1/2009 Plunkett ..... B63G 8/38  
181/200  
2009/0031940 A1\* 2/2009 Stone ..... B63C 11/42  
114/330  
2012/0113756 A1\* 5/2012 Carcaterra ..... G01V 1/3843  
367/144  
2012/0281503 A1\* 11/2012 Rikoski ..... G01C 21/005  
367/88  
2013/0083623 A1\* 4/2013 Brizard ..... G01V 1/3852  
367/15  
2013/0083624 A1\* 4/2013 Brizard ..... B63C 11/42  
367/15  
2014/0107865 A1\* 4/2014 Griffith, Sr. .... G05D 1/00  
701/2  
2014/0177387 A1\* 6/2014 Brizard ..... G01V 1/3808  
367/15  
2014/0301161 A1\* 10/2014 Brizard ..... B63G 8/001  
367/15  
2014/0365258 A1\* 12/2014 Vestal ..... G06Q 10/063114  
705/7.15  
2015/0202770 A1\* 7/2015 Patron ..... G05D 1/024  
700/245  
2015/0276959 A1\* 10/2015 Grimsdale ..... G01V 1/3835  
701/21  
2015/0331421 A1\* 11/2015 Brunet ..... G05D 1/0692  
701/23  
2016/0353238 A1\* 12/2016 Gherardi ..... H04W 4/021

\* cited by examiner



**1****MULTI-ROBOT GRADIENT BASED  
ADAPTIVE NAVIGATION SYSTEM****CROSS-REFERENCE TO RELATED  
APPLICATIONS**

This application claims priority from U.S. Provisional Patent Application 62/016,845 filed Jun. 25, 2014, which is incorporated herein by reference.

**STATEMENT OF GOVERNMENT SPONSORED  
SUPPORT**

This invention was made with Government support under grant (or contract) no. CNS-0619940 awarded by the National Science Foundation. The Government has certain rights in the invention.

**FIELD OF THE INVENTION**

This invention relates to adaptive navigation systems for mobile robots.

**BACKGROUND OF THE INVENTION**

Multi-robot systems have the potential to dramatically impact robotic applications through improved performance and the enabling of completely new capabilities. Alone, robots offer strength, speed, precision, repeatability, and the ability to withstand extreme environments. Combined in a multi-robot system, additional advantages are possible, such as redundancy, increased throughput, expanded coverage/availability, and spatially-distributed sensing and actuation. Multi-robot systems can support applications ranging from remote and in situ sensing to the physical manipulation of objects, and the domains for such applications include land, sea, air, and space. The present invention advances the navigation for such multi-robot systems.

**SUMMARY OF THE INVENTION**

This present invention provides a gradient-based multi-robot technique for adaptively navigating within a parameter field. To implement this technique, simultaneous measurements of the parameter are made at different locations within the field by a spatially-controlled cluster of mobile robots. These measurements are shared to compute a local gradient of the field. Depending on the task to be achieved, the multi-robot cluster is directed with respect to this direction. Moving in or opposite to the gradient direction allows efficient navigation to local maxima/minima in the field, a capability of interest for applications such as detecting pollution sources or the location of resource-starved areas. Moving perpendicular to the gradient direction allows parameter contours to be navigated, a behavior useful for applications such as defining the extent of a field or establishing a safety perimeter at a defined field level. This invention describes the multi-robot control technique which combines a full degree-of-freedom “cluster space” multi-robot controller with a gradient-based adaptive navigation capability. Verification of the embodiments through field experiments using a fleet of three robotic kayaks is also presented.

This technique has a variety of practical uses and applications. These include, but are not limited to, the following:

1. Finding the maximum location of a quantity of interest.

Within the parameter field, the maximum could be a

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source of pollution (the location of a pipe break in an oil spill, the location of nitrogen-rich fertilizer runoff that damages an ecosystem, a dangerous radiation source, etc.) or a valuable resource (an energy source, the source of radio signals from a lost asset, etc.).

2. Locating the minimal point in a field. This could be the location of very low dissolved oxygen in the marine environment, which can lead to fish kills and harmful algae blooms. It could also represent safe locations, such as in a radiation field.

3. Locating and moving along specific contour lines. This capability could support tasks such as tracing out the extent of a field, setting up a patrol along a contour that defines a safety threshold, and so on.

Such capabilities have wide application in areas like environmental monitoring (oil spills, pollution, runoff, health monitoring, etc.), science (underwater hydrothermal vents, geochemical plume tracing, locating topographic/bathymetric features of interest, etc.), disaster response (locating sources of radiation or contamination, etc.), communications (dynamically maintaining optimal communication links, finding optimal locations for wireless networking router placement, finding optimal communication paths in changing fields, etc.), homeland security/national defense (locating radar sources, going to locations of minimum probability of discovery, traveling paths of minimal susceptibility, etc.).

There are many advantages to the use of this technique. These include, but are not limited to, the following:

1. A conventional approach to navigating to a feature in a parameter field (like the location of maximum concentration) requires a two-step process in which the entire region is first surveyed in order to identify the feature of interest and then navigation to that location ensues. With our “adaptive” technique, surveying the field and navigating to the point of interest are simultaneous; furthermore, the entire region does not need to be mapped. This allows for dramatic savings in time and energy in order to go to the location of interest.

2. The adaptive technique supports navigation to features of interest even in time-varying fields. This is not possible in the conventional two-step map then navigate approach.

3. The multi-robot approach allows for an instantaneous estimate of the gradient direction. Single robot approaches require that the single robot travel through a local path in order to estimate the field gradient; this takes additional time and energy. Furthermore, it will not work with time-varying fields.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 shows according to an exemplary embodiment of the invention the implemented gradient-based cluster space control architecture.

**DETAILED DESCRIPTION**

The implemented gradient-based cluster space control architecture is shown in FIG. 1. The robot cluster is shown on the right, with each robot capable of responding to a robot-specific velocity command. The cluster space control layer is shown in the middle. This controller computes an error-drive cluster velocity command, which is converted to robot-specific velocity commands via the inverse Jacobian transform. The research presented in this paper focuses on the inclusion of the adaptive navigation layer, shown in the grey box on the left. This controller estimates the gradient

direction, determines the desired bearing for the cluster, and specifies the appropriate cluster state space set-points to achieve the desired navigation task.

Other embodiments, further teachings and/or examples related to the invention are described in U.S. Provisional Patent Application 62/016,845 filed Jun. 25, 2014, which is incorporated herein by reference.

What is claimed is:

1. A system for collective navigation of mobile robots, comprising:

- (a) a cluster of mobile robots equipped with sensors, the robots navigating in a space with a desired navigation task;
- (b) a first controller controlling the kinematics of each of the robots; and
- (c) a second controller adaptively and collectively controlling the navigation of each of the robots in the cluster by receiving information from the sensors of all the mobile robots in the cluster and estimating field characteristics comprising gradient direction and/or differential scalar measurements based on all the received sensor information to then determine a desired bearing for the entire cluster of mobile robots, and specifying appropriate cluster state space set-points comprising cluster size and shape to achieve the desired navigation task for each of the mobile robots in the cluster.

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